Experimental study of the process of laser treatment of steel Kh12M

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One of the promising methods for improving the performance of technological tools is laser surface hardening, when metal is heated from the surface, while laser processing processes are characterized by a short exposure time and provide almost complete absence of deformations of the processed products. Tool steel Kh12M was chosen as the material for the study. Thermal hardening of samples, which were made in the form of a rectangular parallelepiped, was carried out on laser technological installations equipped with a continuous CO_2 laser with a power of 1.5 kW. The depth of the laser exposure zone is chosen as the target function, which is an important operational characteristic of a technological tool that affects wear of its working surfaces. Based on the analysis of the results of a preliminary experiment with samples made of steel Kh12M, the values of the technological parameters of laser processing and the thermophysical characteristics of the processed material were determined. An experimental plan was developed, at each point of the matrix of which 3 experiments were carried out, while 72 experiments were conducted to find dependence of the depth of the laser exposure zone. Analysis of the experimental results shows that the maximum hardening depth of samples made of steel Kh12M without melting the surface was 0.75–0.80 mm; greater depth is achieved under conditions that cause melting of the surface. To obtain generalized statistical dependencies, the obtained data were transformed, taking into account the definite dimensionless (generalized) parameters. As a result of mathematical processing of experimental data, the formula was obtained for determining the relative depth of the hardened zone at the specified parameters of laser processing without melting the surface.

Key words: stamping production, technological tools, laser processing, experiment planning, depth of the hardened layer.
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Introduction

Stamping production is widely distributed in different industries; it is stipulated by high productivity of metal plastic forming, well precision of stampings and rather wide dimension range of manufactured components [1–5]. At the same time, operating efficiency of high-capacity equipment significantly depends on stable and reliable operation of technological tools, while its insufficient operating resistance leads to rise of cost of stampings, increase of labour and material expenses for replacement of worn tool and its calibration, lowering of pressing equipment productivity, decrease of yield and increase of amount of rejected products.

Taking into account the introduced sanctions for delivery of the advanced technologies and up-to-date technological equipment, the domestic mining and metallurgical enterprises pay much attention to re-engineering of machines and units being in operation, to putting into practice innovative technologies, as well as to improvement of equipment reliability and quality of products, what can be achieved via re-engineering or replacement of outdated equipment [6–11].

Analysis of operating conditions and causes of shutting down stamping tools showed that wear of working surfaces is considered as the main factor having influence on operating reliability of cold deformation stamps. Different kinds of thermal and chemical-thermal treatment are often used practically for increase of operating resistance of technological tools. These treatment methods provide obtaining of high hardness values for a surface layer and for strength of the main metal volume, with good parameters of ductility and impact toughness [12, 13].

Laser surface hardening is one of the promising methods for increase of technological tools workability; its practical application became possible due to introduction of industrial high-capacity lasers [14–16]. During laser processing, metal heat is realized from the surface, while laser processing processes are characterized by short exposure time and provide almost complete absence of deformations of the processed products.

The aim of this research is experimental examination of laser surface hardening of samples made from Kh12M steel for determination of a hardened zone depth with preset parameters of laser processing without surface melting.

Methods of research

The most widely distributed semi-killed tool steel Kh12M was chosen for research as a die material for cold deformation [17]. Thermal hardening of samples, which were made in the form of a rectangular parallelepiped, was carried out on laser technological installations equipped with a continuous CO_2 laser with a power of 1.5 kW. Preliminary the samples were subjected to conventional volumetric heat treatment including hardening in oil from the temperature 1020–1040 °C and tempering at the temperature 170–200 °C, to provide surface hardness HRC 42-50.

Application of light-absorbing coating is conducted prior to hardening laser treatment; it includes three technological operations – surface cleaning, coating application and drying. Surface cleaning with removal of contaminations, oil and dust was carried out via wiping by acetone or alcohol. Yellow gouache was used as light-absorbing coating, it was applied uniformly at the processing surface by a roller; thickness of applied layer was 20–30 µm. After coating application, it is required to provide drying at the room temperature during 40–50 min.

Drying was accompanied by preparing for the work and switch-on of the laser unit. Powerful CO_2-laser was equipped with low-capacity helium-neon laser and an optical system, which allows to monitor location of a laser spot on the surface of processing tool. Optical way of a low-capacity laser repeats exactly the way of CO_2-laser, thereby tuning by low-capacity and safe beam guarantees precise relocation of powerful emission. Adjusting of dimensions and shape of a laser spot is carried out by focusing with use of an optical lens.

The tool set for laser hardening is mounted on the coordinate worktable, which is able to make translational motion along three coordinates. Then the worktable implements translational motion with preset speed in the laser beam direction, what finalized in thermal hardening.

Microstructure of the laser processing zone was examined using “Neofot-21” microscope with resolving power from 50 to 2,000 times. Microhardness was measured my microhardness meter PMT-3. Heat resistance of steel was assessed via its hardness after heating up to the testing temperature with consequent air cooling.

Experiment planning for laser heat treatment of Kh12M steel

Taking into account the difficulties of building the adequate theoretical models with use of classic heat conduction theory, mathematical models, which were obtained via statistical processing of experimental data, were used in many researches of laser heat treatment processes. The most part of well-known relationships have a common disadvantage that they use as a rule dimension values; in addition, the complex account of influence of different factors on laser processing is often absent. Use of dimensionless parameters and criteria equations of the theory of dimensions and similarity makes it possible to provide more substantiated approach for solving this problem [18–20].

Creation of mathematical models is necessary for development and improvement of laser heat treatment technology. Choice of the optimal parameters is based on search of the response function, what stipulates necessity of choosing the optimization criterion and the goal function.

The goal function should meet the following requirements [21]:

– to present the quantitative characteristic, which determines degree of technological perfection of the chosen method for tool hardening as well as its economical profit;

– to be a single-valued function when input parameters are varied;

– to have simple and clear physical significance and to be the only function.

Based on the above-described criteria, depth of the zone of laser exposure is chosen as the goal function, it is an important operation parameter of technological tools for metal forming.

It was established that the following two groups of factors have influence on laser hardening process [15, 16].

1. Technological parameters of laser processing: laser emission capacity P, kWt; laser ray diameter d_r, mm; laser beam relocation speed in relation to a component V, mm/s; absorption coefficient of applied coating K_{abs}.

2. Thermal physical parameters of processing materials: temperature conduction coefficient a, mm²/s; heat conduction coefficient λ, Wt/(mm·°C); melting temperature T_{mel}, °C; hardening temperature T_{quen}, °C.

Based on analysis of the results of preliminary experiment with samples from Kh12M steel, which correlate well with well-known data from scientific and technical literature, the following values of parameters were used in consequent researches: light absorption coefficient $K_{abs} = 0{,}6$; heat conduction coefficient $\lambda = 28$ Wt/(mm·°C); temperature conduction coefficient $a = 7.78 \cdot 10^{-6}$ mm²/s; melting temperature $T_{mel} = 1400$ °C; hardening temperature $T_{quen} = 1000$ °C.

Taking into account possibilities of optical systems in laser units, laser ray diameter was accepted to be constant and equal to $d_r = 4$ mm.

Maximal laser beam relocation speed V_{max} along the surface of processing tool is determined by technical parameters of the used laser complex. We accepted $V_{max} = 2$ m/min ≈ 33 mm/s in our experiments. Minimal laser beam relocation speed V_{min} depends on the concrete experimental conditions; it is accepted to be equal to zero for the ultimate stationary case (i.e. when $t \to \infty$).

Assessment of the area of laser emission capacity P variation was determined from the condition, when the minimal value of capacity density q_{min} corresponds to a stationary heating case; then the temperature on the surface of processing metal will be equal to the hardening temperature, with rather large time of laser exposure [15, 16].

$$q_{min} = \frac{2 \cdot \lambda \cdot T_{quen}}{d_r} = \frac{2 \cdot 0{,}028 \cdot 1000}{4} = 14 \text{ Wt/mm}^2.$$

Thereby the minimal capacity value P_{min} is equal to 0.29 kWt.

The value of maximal density of capacity q_{max} for laser emission, when surface temperature in a ray center achieves the metal melting temperature, makes 33.3 m/s for maximal relocation speed of laser beam.

It should be noted that presented relationships can be taken into account only for approximate assessment of density of laser emission capacity, because several admissions were used during their conclusion. To provide more exact determination of maximal and minimal values of capacity and speed, a preliminary experiment was carried out and the following variation ranges were chosen on its base:

$P = 0.52 - 1.45$ rWt; $V = 6 - 33$ mm/s.

In correspondence with the above-described recommendations, the experimental plan was developed. It was aimed on examination of the process and determination of the optimal conditions of laser hardening without surface melting of processing material. 3 experiments were planned in each matrix point; for this purpose, double laser processing was conducted on the surface of steel Kh12M samples – along three parallel paths with distance between them $s > 2 \cdot d_r = 8$ mm. In this way, 72 experiments were carried out to determine influence of laser exposure zone depth; the results are presented in the **Table 1** and **Fig. 1**.

Obtained results

Analysis of the experimental results shows that the maximal hardening depth for Kh12M steel samples makes $h_{hard} = 0.75–0.80$ mm (without surface melting). Large depth of hardened zone ($h_{hard} = 1.15–1.35$ mm) is achieved under the conditions causing surface melting. It should be noted that depth of hardening is determined with essential error when dimensions of laser exposure are small, what means small capacity of laser emission and high speed of laser beam relocation.

To conclude generalized statistic relationships, the obtained data were transformed taking into account consequent dimensionless (generalized) parameters [22]:

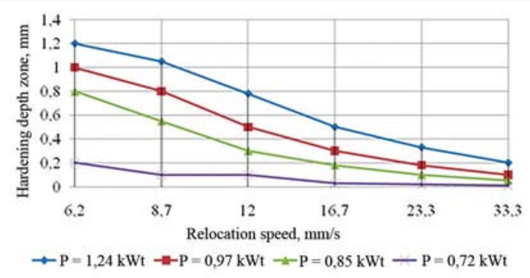

Fig. 1. Relationship between hardening depth hhard and laser beam relocation speed *V* with different laser emission capacity *P*

1) the coefficient of laser paths overlapping

$$S^* = \frac{S}{d}$$

2) relative capacity of laser processing

$$P^* = 2 \cdot \frac{K_{abs}}{d \cdot \lambda \cdot T_{mel}}$$

3) relative speed of laser beam relocation

$$V = \frac{V \cdot d}{4 \cdot a}$$

4) relative depth of hardened layer

$$Z = \frac{4 \cdot h_{hard} \cdot P}{\pi \cdot d^2 \cdot (T_{mel} - T_{hard}) \cdot \lambda},$$

Table 1. **The matrix of experiment planning for laser processing of steel Kh12M**

No. of matrix point	Parameters of laser processing		Depth of hardening zone, h_{hard}, mm
	Capacity of laser emission *P*, kWt	Speed of laser beam relocation *V*, mm/s	
1	1.24	33.3	0.1
2		23.3	0.2
3		16.7	0.5
4		12.0	0.8
5		8.7	1.0*
6		6.2	1.3*
7	0.97	33.3	0.1
8		23.3	0.1
9		16.7	0.3
10		12.0	0.5
11		8.7	0.8*
12		6.2	1.1*
13	0.85	33.3	0
14		23.3	0
15		16.7	0.1
16		12.0	0.2
17		8.7	0.6
18		6.2	0.9
19	0.72	33.3	0
20		23.3	0
21		16.7	0
22		12.0	0.1
23		8.7	0.1
24		6.2	0.2

* – experiments, when surface melting occurred

where S — distance between laser paths, m; d — beam diameter, m; K_{abs} — absorption coefficient; P — capacity of laser emission, Wt; λ — heat conduction coefficient, Wt/(m·K); T_{hard} and T_{mel} — hardening and melting temperature respectively, °C; V — speed of laser beam relocation, m/s; a — temperature conduction coefficient, m²/s; h_{hard} — depth of hardened layer, m.

Let us explain the physical meaning of these parameters.

Overlapping coefficient S^* characterizes influence of consequent neighbor laser paths on previous ones: when $S^* < 1$, the paths are overlapped and material structure in the previous area of laser exposure changes; when $S^* > 2$, we can ignore mutual effect of neighbor laser paths. Thereby this condition is used often in laser hardening of technological tools for metal processing.

The value P^* corresponds to the relationship between efficient capacity of laser emission $P_{eff} = K_{abs}\cdot P$ and capacity which can be removed from the surface owing to heat conduction inside metal without its melting.

The value V^* is equal to relationship between speed of laser beam relocation and speed of temperature front distribution in the material.

The relationship between the depth of hardened layer h_{hard} and maximal possible theoretical value h_{max} is approved as a relative value Z^*; it can be achieved in the case when metal surface temperature corresponds to its melting temperature.

Corresponding relationships between dimensionless depth of hardened zone Z^* and dimensionless speed V^* for various values of laser emission capacity P are shown in the **Fig. 2**.

It can be seen that the curves have inflection points for small values of V^*; their appearance can be explained by the fact when surface metal temperature achieves the liquidus point, thereby laser processing accompanies by surface melting. Respectively, the relationship between the depth of hardening area with melting and without melting is described by different formulas, what is stipulated by variation of the mechanism of physical-chemical processes.

Mathematical processing of the experimental data finalized in the following formula for determination of the relative depth of hardened zone for preset parameters of laser processing without surface melting:

$$Z = 0.00649\cdot\left(P\right)^{2,33}\cdot\left(V\right)^{-2,0}$$

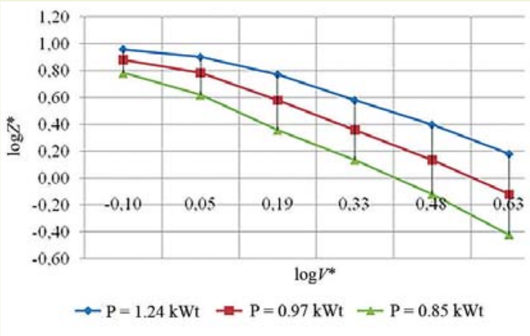

Fig. 2. Relationship between dimensionless depth of hardened zone Z* and dimensionless speed V* of laser beam relocation for various values of laser emission capacity P*

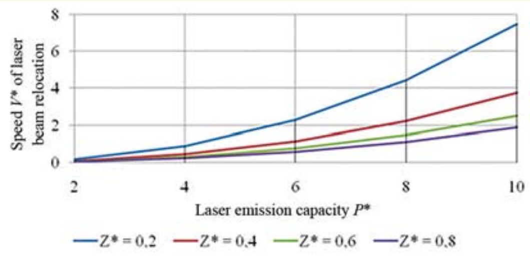

Fig. 3. Lines of equal levels for relative depth of hardening zone Z*

To provide more suitable practical use, this relationship can be expressed as the lines of various levels $Z^* = \text{const}$ (**Fig. 3**).

Laser heat treatment of tool steel Kh12M should be conducted in such way, that the surface temperature of processed metal T_{surf} is located within the range $T_{hard} < T_{surf} < T_{melt}$. To provide approximate selection of corresponding values of laser emission capacity P and laser beam relocation speed V, we can use the diagram displayed in the **Fig. 4**.

It should noted that the results, which were obtained in our experiments, correlates well with the results of other authors; that's why use of dimensionless parameters, which were suggested in this research, allows to describe regularities of laser hardening for different steel grades in uniform way.

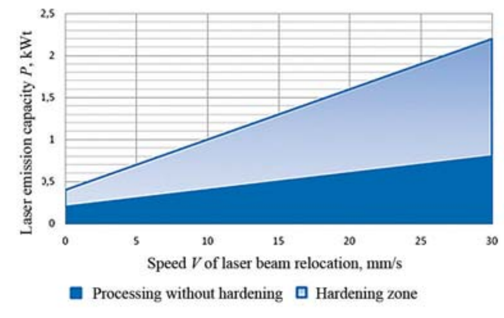

Fig. 4. Location of the hardening area for 12KhM steel without surface melting

Generally, Kh12M steel microstructure in the laser exposure zone can be divided in three main areas: melting area (obtained during hardening from molten state), hardening area (obtained from solid phase during heating up to the temperature above Ac1 point) and transition area (tempering without preliminary hardening).

Conclusion

The results of experimental investigation of laser surface hardening for samples from Kh12M semi-killed tool steel was carried out on laser technological installations equipped with a continuous CO_2 laser with a power of 1.5 kW. The depth of the laser exposure zone is chosen as the target function, which is an important operational characteristic of a technological tool that affects wear of its working surfaces. Based on the analysis of the results of a preliminary experiment with samples made of steel Kh12M, the values of the technological parameters of laser processing and the thermophysical characteristics of the processed material were determined. An experimental plan was developed, at each point of the matrix of which 3 experiments were carried out, while 72 experiments were conducted to find dependence of the depth of the laser exposure zone. Analysis of the experimental results shows that the maximum hardening depth of samples made of steel Kh12M without melting the surface was 0.75–0.80 mm; greater depth is achieved under conditions that cause melting of the surface. To obtain generalized statistical dependencies, the obtained data were transformed, taking into account the definite dimensionless (generalized) parameters. As a result of mathematical processing of experimental data, the formula was obtained for determining the relative depth of the hardened zone at the specified parameters of laser processing without melting the surface.

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